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Review Article

A Review on Different Approaches of Developing Environment Friendly Drilling Fluids

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ABSTRACT

In the drilling industry, environmental pollution has always been a serious problem while working with drilling fluids. Due to increasing environmental awareness, Drilling fluids containing harmful non degradable and aromatic content are banned in many environmentally sensitive areas. Over the years, many approaches were used to satisfy the environment protection laws and recent development involves using environmentally acceptable additives to formulate drilling fluids, which have been applied to meet the stringent environmental regulations, while at the same time fulfilling the increasingly challenging drilling conditions. This paper reviews some of the environment friendly approaches as well as recent advances using nanoparticles focusing on the improvement of drilling fluid performance.

Keywords: Drilling fluid; Environment friendly drilling fluid; Environment pollution; Nanoparticles

Abbrevations: DIF: Drill in Fluids; EPA: Environmental Protection Agency; HSE: Health Safety and Environment; HPHT: High-Pressure High-Temperature; HPWBF: High-Performance Water-Based Drilling Fluids; HPWBM: High-Performance Water-Based Mud system; MEG: Methylglucoside; OBM: Oil Based Mud; NDDF: Non Damaging Drilling Fluids; PHPA: Partially-Hydrolyzed Polyacrylamide; ROP: Rate of Penetration; SBM: Synthetic Based Mud; WBM: Water Based Mud; WBDF: Water Based Drilling Fluid

INTRODUCTION

Drilling fluids, also known as drilling mud, is a heavy, viscous fluid mixture that is used in oil and gas drilling operations to transport drilled cuttings to the surface and also cooling and lubricating the drill bit and drill string. It counterbalances the hydrostatic pressure to prevent the formation fluids from entering the wellbore and keeping the wellbore stable. It should do all these while minimizing damage to the producing formation. Moreover, drilling fluids must satisfy three important requirements: they should be easily usable, inexpensive and environmentally safe [1].

Mandal, et al., have made the following suggestions which nicely sum up the points to be considered while designing an environmentally friendly drilling fluid.

- Non-degradable fine solids should be avoided while designing the drilling fluid.
- It should be able to reduce filtration loss and minimize the amount of drilled fine solids.
- It should not chemically react with formation fluid to form insoluble precipitate.
- It must contain inhibitive filtrate which would not swell the clay envelopes around pay zone particles.
- Polymer particles' invasion into the pay zone should be prevented by bridging exposed pore openings with the help of specialized sized materials.
- It should deposit an easily removable non-damaging filter cake.
- It should lower overall cost and optimize production while following HSE regulations.

Oil-well drilling requires different types of drilling fluids for different situations. It can be classified into three broad groups: Oil-based, water-based and gaseous. Barring the gaseous fluids that are used for underbalanced drilling which present unique challenges, each group has some basic characteristics that can be

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modified with certain additives, making them suitable for a range of drilling conditions. The factors that guide the selection of mud additives and drilling fluids are complicated and inter-related. The challenge is to design a formulation of base fluid and additives that can provide the critical density and rheology parameters, while being environmentally friendly. In order to design such drilling fluid, various approaches have been going on since the 1980's, and some of these approaches will be discussed in this paper [2].

LITERATURE REVIEW

Oil based drilling fluids

Since the early 1960's, oil-based drilling fluids have been used in technically demanding wells. Oil based muds stabilize the borehole and allow faster penetration rates. One of their most important features is their high lubricity. However, the low biodegradability, high toxicity nature of aromatic compounds causes severe impact on marine life. In 1978, all oil companies received a wakeup call when the U.S Environmental Protection Agency (EPA) proposed a testing procedure using Mysid shrimp for assessing toxicity of drilling fluid and additives. Also in 1978, the State of Alabama enforced discharge regulations on oil companies drilling in Mobile Bay [3].

These environmental regulations forced the oil companies to look for new drilling fluid systems. A new drilling fluid using non-toxic mineral seal oil as the base fluid was proposed by A.A. Hinds and W.R. Clements in 1986. Boyd, et al., suggested low-viscosity base fluid for low-toxicity oil-mud systems which improved the penetration rates (ROP's), reduced mud-treatment costs, and provided better borehole stability. Hodder, et al., proposed the use of palm oil derived systems as drilling fluids, which showed excellent thermal resistance in laboratory tests [4].

When selecting mud additives such as chemicals, polymers, salt-water and oil-based muds, both technical and environmental factors should be considered to reduce environmental impact. Some additives that are considered environment friendly may not be tolerable in the future due to increasingly strict environmental legislations. Some of the additives may only show their adverse effects when subjected to long term exposure. The common chemical additives including potassium chloride, potassium sulphate, polyamine, chromium-containing thinners etc. have an overall negative environmental impact and are expensive [5].

Synthetic based mud: Synthetic-Based Muds (SBM) are invert emulsion muds in which synthetic fluids are used as a continuous phase instead of oil. Popular fluid types include several olefin oligomers of ethylene. Esters made from vegetable fatty acid and alcohol were among the first such fluids. Esters show low levels of toxicity, are biodegradable in both aerobic and anaerobic conditions, and highly lubricating in nature. In recent years, starch ester from mango starch kennel was successfully produced and it was found more thermally stable than its precursors and the drilling fluid prepared with starch ester as additive presented excellent electrical stability as well as higher rheological parameters and lower volume of filtration under HPHT conditions when compared to the one prepared with the commercial additive.

Another approach uses novel oil-in-water drilling mud formulated with extracts from Indian mango seed oil and comparisons of rheological and filtration properties showed better results than diesel oil. From the Figure 1, it can be seen that apparent viscosity, plastic viscosity, Yield strength, initial and final gel strength increases in case of Indian mango methyl ester emulsion mud as compared to diesel emulsion mud. The fluid loss decreases in the newly developed drilling mud [6].

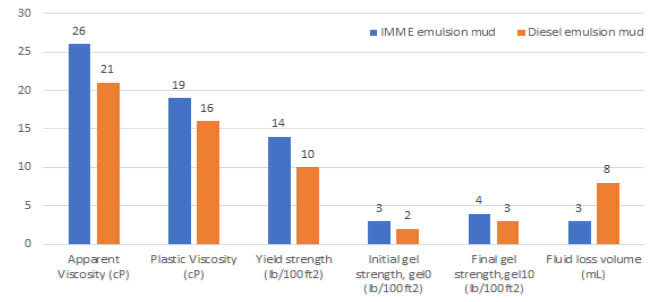

Figure 1: Comparison of properties of the drilling fluids prepared with Indian Mango Methyl Ester (IMME) and diesel oil-based mud.

Synthetic Based Mud (SBM) was developed as an alternative to mineral and diesel-based oil muds with the purpose of reducing the environmental impact of discharging cuttings to the seafloor. Fadairo, et al., reviewed the environmental impact of drilling fluid and after a number of tests concluded that synthetic oil-based muds are technically and environmentally viable replacements for conventional oil-based muds. Neff, et al., studied the environmental impacts of Synthetic Based Muds (SBM) and found that because of the adherent SBM base chemicals, the cuttings are hydrophobic and clump together after discharge to the ocean. The clumps of SBM cuttings, being denser than seawater, settle rapidly to the sea floor. The cuttings accumulate on the seafloor near the discharge point depending on water depth, current speeds, and density and degree of clumping of the cuttings. Because of the rapid descent of the cuttings, very little SBM base chemical dissolves or is dispersed in the water column and concentrations are quickly diluted to below toxic levels [7-10].

Bio-based mud: Many attempts of using biodegradable organic oils as the base fluid have been going on since the 1980's and some of them have been successfully implemented in the field. Compared to the synthetic based drilling fluids, the vegetable oil or bio-based drilling fluids show poor performance results. The drilling fluids formulated from pure vegetable oils fail to fulfill the technical requirements of a drilling fluid due to its excessive viscosity and poor thermal stability.

The research area of determining a substitute for the conventional diesel oil-based fluid to meet the environmental specifications has been going since last decade. Various attempts on this field showed that organic oils like *Jatropha* oil, rapeseed oil, cottonseed oil etc. can be used as an alternative to diesel oil or mineral oil. Fadairo et al. studied the formulation of Algae, Jatropha, Moringa, Canola oil-based mud that can carry out the same functions as diesel oil-based mud and equally meet up with the HSE (Health, Safety and Environment) standards. Table 1 shows the rheological properties of different plant oil-based mud compared to diesel oil-based mud [11-13].

Table 1: Rheological properties of diesel, *Algae, Jatropha, Moringa* and *Canola* oil-based mud.

Rheological properties	Diesel	*Algae*	*Jatropha*	*Moringa*	*Canola*
Plastic viscosity	15	8	21	11	8
Apparent viscosity	92.5	61	77	84.5	64
Gel strength	50/51	52/43	54/55	52/53	60/72

From the Table 1, the lower viscosities of *Algae*, *Moringa* and *Canola* makes them suitable alternatives for diesel oil-based mud. The plastic viscosity of *Jatropha* can be lowered with the help of adequate concentration of thinners. Similarly, this method can also reduce the gel strengths of these plant oil-based muds. The toxicity behavior was studied using corn seeds and bean seedlings, to see the effect on plant growth. The results showed that these plant oil-based muds show less toxicity than diesel oil-based mud. The comparison of plant growth rate and number of days of survival of bean seed when exposed to diesel oil-based mud and *Jatropha* oil-based mud can be seen in Figure 2.

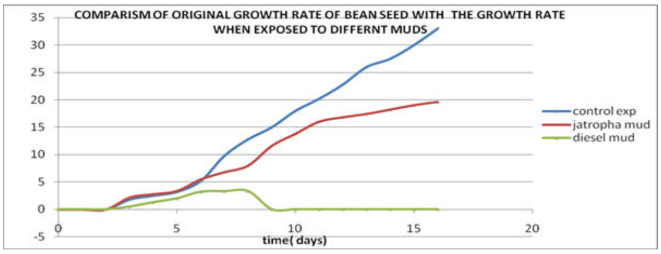

Figure 2: Plant growth rate comparison with diesel and *Jatropha* oil-based mud.

Another research using *Jatropha* oil as replacement for diesel oil showed that, plant-based oils such as *Jatropha* oils are renewable, highly degradable alternatives for diesel oil-based mud due to its higher flash point, better thermal stability and lower toxic compositions compared to diesel-based muds [14].

The excessive viscosity and poor thermal stability of pure vegetable oil was a hindrance in the development of bio-based oil drilling mud. In order to improve the thermo-physical traits of bio-based oil drilling fluids, Chai et al. tried using carbon-based nanoparticle additives and found that adding graphene oxide with hydrogenated oil can enhance the thermal conductivity and improve the rheological properties of bio-based oil drilling fluid. Presence of oxygenated functionalities in graphene oxide makes it easily dispersible in water and other organic solvents, as well as in different polymer matrices, which makes it versatile for production of nano-fluids with a broad range of applications.

Water-based drilling fluids

Since the 1990's, environmentally and economically acceptable water-based drilling fluids have been developed where environmentally friendly additives are used as Viscosifier or fluid loss control agents. Water is the first choice for base fluid while designing drilling fluids for normal operations, as it is non-toxic and relatively easier to dispose of. Figure 3 shows the percentage weight comparison of water base mud and non-aqueous drilling muds [15].

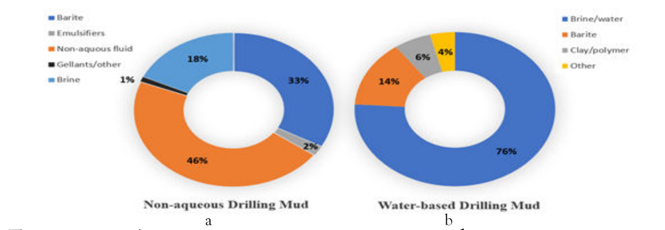

Figure 3: Approximate percentage weight composition of typical: (a) Non-aqueous drilling fluids; and (b) Water-based mud.

In challenging drilling conditions, however, Water-Based Mud (WBM) shows less efficient results than oil-based mud. Therefore, various approaches have been taken to improve thermal stability, fluid loss control and rheological properties enhancement, prevent formation damage, borehole instability etc. Some of these approaches are mentioned below.

Thermal stability

In Europe, due to environmental regulations, chrome-lignosulphonates were restricted and it led to the development of a chrome-free, high-density High-Pressure High-Temperature (HPHT) water-based fluid system. Clay and synthetic polymers were used to provide excellent fluid-loss control and to generate thermally stable rheology. Extensive testing showed that the use of highly efficient dispersants prevents high-temperature gelling and improves fluid resistance to drill solids contamination. It also helped to solve the problem of high temperature and pressure instability of environmentally friendly water-based drilling fluids. Polyvinyl alcohol is one of the most desirable polymers for recent drilling fluid designing as it has proved to improve mud thermal stability while positively influencing mud rheology and cake filtration. Recent developments are going on using nanoparticles to improve thermal resistance of drilling mud without significantly changing rheological properties. One such approach uses laponite nanoparticles and various derivatives of natural materials, including crosslinked starch, cellulose composite, gelatine ammonium salt, poly-l-arginine, and polyanionic cellulose, to design a kind of Environmentally Friendly Water-Based Drilling Fluid (EF-WBDF) for drilling in environment-sensitive areas. Experimental results showed that EF-WBDF displayed satisfactory thermal resistance up to 150°C, and the rheological properties did not suffer significant fluctuation, showing potential application in high-temperature wells. In another approach, nano-grafted acrylamide copolymer was used to design an anti-temperature and anti-calcium fluid loss agent for WBDF. After laboratory tests, this fluid loss agent was found to withstand a high temperature of 220°C, with the freshwater-based mud filtration volume at this temperature being 13.25 mL. Also, at 180°C, AAN-g-SiO_2 showed resistance to calcium and salt [16].

Borehole instability

With the development of drilling technology, well structures are becoming more complex and operating environments are becoming harsher. WBDFs have difficulty in meeting the requirements for coping with these complicated situations. It leads to the problem of borehole instability. One of the earlier approaches was to use MEG (Methyl Glucoside) drilling fluid formulated to act like an Oil-Based Mud (OBM) in preventing hydration, pore-pressure increase, and weakening of shale. MEG drilling fluid system has similar lubricity and maintenance of borehole stability with OBM, while being easy to formulate and condition, and is non-toxic and environmentally benign. Further studies showed that MEG drilling fluid has advantages in caving prevention, lubricity, solid carrying and formation damage controlling and it can minimize the environmental effects. Due to its effect in improving Shale inhibitive performance, controlling fluid loss, reducing mud cake thickness and permeability with increase in MEG concentration, it is still being used as an alternative to oil-based mud [17-19].

Shale instability is one of the main causes of borehole instability. The invasion of poorly managed WBDFs into shale formations will increase the pore pressure and weaken the rock strength. Clay swelling could occur when the water and ionic compound are absorbed, resulting in borehole collapses and stuck pipes. These borehole issues often result in poor Rate of Penetration (ROP), reduction of drill cuttings transport, borehole collapse and increased Equivalent Circulating Density (ECD) that ultimately leads to non-productive time. Shale instability will increase the risk of wellbore collapse and the costs for overall drilling operation will be higher. However, formulation of drilling fluid with suitable shale inhibitors can reduce these shale instability issues. KCl is the most common shale inhibitor utilized in various water-based drilling fluid systems. KCl can prevent clay swelling by ion exchange, but the high concentrations of Cl^- in WBM can cause environmental problems.

Environment friendly shale inhibitor: Oil India Limited (OIL) used an amine-based glycol-amine-PHPA (partially-hydrolyzed polyacrylamide) inhibitive mud in drilling high tech horizontal wells in its Assam field, which replaces the former objectionable Potassium Chloride (KCl) system. Following this, several researchers developed variety of conventional shale inhibitors like polyethylene mine, Xanthan gum and polyanionic cellulose and eco-friendly carboxymethyl chitosan. However, the polymer degrades at high temperature conditions; therefore it may not be a viable option in high temperature wells.

In recent years, a large number of studies on low-toxicity and bio-environmentally friendly shale inhibitors have emerged, which includes acrylamide-based polymeric shale inhibitors, biomolecule and biosurfactant inhibitors, dendrimer shale inhibitors, low molecular amine-based shale inhibitors, salt and alcohol inhibitors and synthetic polymer inhibitors. Based on the structure of these inhibitors, inhibitory mechanism, inhibitor type, and their compatibility in drilling fluids, the environmentally friendly shale inhibitors can be represented by the following Table 2.

Table 2: Environmentally friendly shale inhibitors: Mechanism and effects.

Author	Inhibitor	Inhibitor type	Mechanism	Rheological properties/ compatibility
Aghdam et al.	*Seidlitzia rosmarinus* Leaf and Stem Extract (SRLSE)	Biomolecule and biosurfactant inhibitor	A hydrophobic shell was formed between the hydrophilic tail of saponin (a dominant constituent of SRLSE) and MMT's surfaces.	SRLSE was compatible with conventional WBDF additives.
Cescon et al.	Cationic starch derivatives (CAT2)	Synthetic polymer inhibitor	Adsorption and cation exchange.	CAT2 is a biodegradable inhibitor and it would not destroy the basic performance of the fluid, while performing its purpose.

Chen et al.	Amine-Tartaric Salt (ATS-4)	Low molecular amine-based shale inhibitor	Adsorption and intercalation through electrostatic attraction and hydrogen bonding.	ATS-4 exhibited excellent compatibility with the modified starch in water-based drilling fluids.
Chu et al.	Si-HPEI	Dendrimer shale inhibitors	Siloxane groups made Si-HPEI form firm and stable chemical adsorption on the clay surface.	Had no negative impact on other properties of the drilling fluid.
Fritz and Jarrett	Soluble potassium silicate	Salt inhibitors	Surface adsorption and chemical reaction of soluble potassium silicate on formation surface.	This new silicate-treated WBDF has been widely accepted for use in Fayetteville shale.
Ghasemi et al.	Korean red Ginseng root extract	Biomolecule and biosurfactant inhibitors	Ginsenoside was adsorbed on bentonite through hydrogen bonding and formed a hydrophobic layer.	The biosurfactant was compatible with all the additives.
Ibrahim and Saleh	AC-D/PVP composite	Dendrimer shale inhibitors	A polymer film is formed on the clay surface, the electrostatic interaction and hydrogen bonding enhance the formation of the polymer film and the adsorption on the clay surface.	It will not significantly affect the rheology of the drilling fluid.
Jain and Mahto	Polyacrylamide/diallyl dimethyl ammonium chloride-grafted-gum acacia copolymer	Acrylamide-based polymeric shale inhibitors	The protonated ammonium ions adsorb on the clay surface and form a surface coating.	This biopolymer is non-toxic and showed good filtration and rheological properties.
Li et al.	Gelatin Quaternary Ammonium Salt (GT)	Biomolecule and biosurfactant inhibitors	Electrostatic attraction, hydrogen bonding.	GT could perform good compatibility and inhibition in WBDFs.
Li et al.	Poly-L-arginine (PArg)	Biomolecule and biosurfactant inhibitors	Electrostatic adsorption and hydrogen bonding make PArg encapsulate bentonite particles.	PArg had good compatibility and inhibition.
Li et al.	PGly, PGlu, PLys, and PArg	Biomolecule and biosurfactant inhibitors	PGly and PGlu mainly reduce the degree of clay swelling, while PLys and PArg mainly reduce the degree of clay dispersion	Results showed good compatibility and inhibition.
Ma et al.	Chitosan-Grafted L-Arginine (CA)	Biomolecule and biosurfactant inhibitors	CA encapsulated bentonite and shale surfaces.	CA will not affect the rheology and can reduce fluid loss.
Moslemizadeh et al.	Triterpenoid saponin (GGRE)	Biomolecule and biosurfactant inhibitors	GGRE formed a hydrophobic shell on the surface of bentonite.	GGRE was compatible with common additives.
Nikolaev et al.	Composite of PEG and PrG	Alcohol inhibitors	Inhibit hydrate nucleation and aggregation.	The non-toxic compound alcohol drilling fluid showed good low-temperature rheology, density and lubricity.

Song et al.	Polyammonium (DEP-7)	Low molecular amine-based shale inhibitor	Electrostatic interaction and hydrogen bonds.	DEP-7 was compatible with the conventional additives in drilling fluids.
Wang and Pu	Hydroxyl-Terminated Hyperbranched Polymer (β-CD-HBP-OH)	Dendrimer shale inhibitors	The hyperbranched structure and a large ofnumber terminal hydroxyl groups provide uniform adsorption.	β–cyclodextrin and glycerol carbonate are non-toxic and showed favorable rheological properties.
Xie et al.	Branched polyethyleneimine (BPEI)	Dendrimer shale inhibitors	Insert between the layers of bentonite and replace the interlayer sodium ions.	An effective balance was achieved between swelling inhibition and the rheology of water-based drilling fluids.
Zhang et al.	Ammonium–Lauric Salt (ALS-2)	Low molecular amine-based shale inhibitor	Electrostatic interaction and surface modification.	ALS-2 was compatible with conventional additives.
Zhang et al.	Pomelo peel powder	Biomolecule and biosurfactant inhibitors	The active substances in fresh pomelo peel powder hinder the hydration and swelling of clay.	Fresh pomelo peel powder can improve the rheological and filtration properties.

Nano-particles as shale inhibitor: Nano-Particles (NPs) have now emerged as suitable additives to improve the borehole stability. For wellbore stability maintenance, best way to prevent pressure increase at near wellbore is by pore throat physical plugging and building a fine impenetrable mud cake on the wellbore wall. To build an impermeable mud cake on shale, additive particle size should be smaller than the size of shale pore throats. Hence nanomaterial additive has been introduced in the WBDF formulations. NPs also reduce torque and drag as they reduce friction between drill pipe and borehole wall. For drilling unconventional shale plays located in environmentally sensitive areas, a new environmentally safe and economically acceptable water-based drilling fluids approach was taken. Chloride-free and environment-friendly additives are used to control the different factors like fluid performance, wellbore stability and drilling performance. This technology used nano-particles designed to plug the pores and micro-cracks present in the shale formations. With the help of nanotechnology, an environmentally friendly fluid system achieving shale stabilization was developed and this High-Performance Water-Based Mud system (HPWBM) helps stabilize the reactive clays/shale by reducing pore pressure transmission with the help of specially designed chemical components. In HPWBM, the drill cuttings and effluents can be discharged offshore due to absence of oil contamination. It is one of the first commercial applications of nanotechnology in drilling fluids.

Several researchers have studied the effects of different nano-particles like SiO_2-xanthan nanocomposites, glucopyranose modified graphene (Glu-Gr), nano silica grafted hyperbranched polyethyleneimine (HPEI-silica), nanoscale laponite, SDNL (latex polymer N.P.) for shale stability improvements which are summarised in the Table 3.

Table 3: Nano-particles as shale inhibitors: Experimental conditions and findings.

Author	Type of nano-particles	Properties tested	Experimental conditions	Findings/Results
Ali et al.	SiO_2/KCl/xanthan nanocomposites	Linear swelling	Ambient and HPHT	By adding 4000 ppm of SiO_2/KCl/xanthan N.C.s and KCl, shale swelling was decreased by 41 and 52.2%.
Huang et al.	Nanoscale Laponite	Immersion test, linear swelling, shale recovery	Ambient	Laponite N.P. was able to plug the shale pores due physically and chemically to electrostatic interaction, low free water contents and excellent thixotropy.

Rana et al.	Glucopyranose modified graphene (Glu-Gr)	Shale dispersion	LPLT	Glu-Gr WBDF displayed lower fluid loss and having high dispersion recovery rate as compared to base drilling fluid.
Xu et al.	SDNL (latex polymer N.P.)	Linear swelling, shale recovery	HT	2% SDNL had a linear growth rate of 4.9% and a recovery rate of 93.7% in the shale sample.
Zhong et al.	Nanosilica grafted hyperbranched polyethyleneimine (HPEI-silica)	Shale dispersion, linear swelling	HT	HPEI-silica has swelling rate of 40.5%, much lower than pristine nano silica.

RESULTS AND DISCUSSION

Formation damage prevention

Some water-based drilling fluids used before the 1990's showed drilling and completion related formation damage. To prevent the fluid invasion to the production zone, Drill-in Fluids (DIF) was introduced in the early 1990's, to reduce drilling and completion induced damages, especially in horizontal open whole completions. Drill-in fluids contained solid materials as bridging agents to plug the surface of a formation matrix and as weighting material to control formation pressure. However, further field testing proved that the solid content of drilling fluid affects the performance of the well. If drilled solids were kept in low concentration, then the open hole performed better and if solid control was not achieved, significant formation damage occurred. One approach was done using polymer as bridging agents to control the fluid loss and filter cake formation, thereby preventing formation damage. Use of polymers instead of solid materials helped achieve good solid control. Tamarind gum and tragacanth gum are two such eco-friendly and inexpensive polymers suitable for drilling fluid formulation.

To provide good solid control using bio-degradable polymer and to produce an easily removable external fluid cake, a Non-Damaging Drilling Fluids (NDDF) were developed by ONGC. NDDF increases oil production by controlling formation damage during drilling. NDDF was introduced in the Linch field, Mehsana asset of ONGC, in North Cambay Basin in India, as a part of paradigm shift, emphasizing the use of new technologies to increase oil production. Laboratory results as well as field behaviour of NDDF parameters showed high compatibility with drilling parameters and no complications were faced while drilling and testing, with a major benefit of increased oil productivity. The composition of prepared NDDF is shown in Table 4.

Following the NDDF approach, another approach used fly ash, xanthan gum, polyanionic cellulose and starch as bridging materials instead of calcium carbonate. After different experimental studies, it was observed that drilling fluids developed using fly ash as bridging agent have maintained good rheological properties and have better control on fluid loss and filter cake thickness than calcium carbonate.

However, these NDDF contained KCl as we can observe from the Table 4, and it can cause environmental problems. Therefore, recent studies are going on using environmentally friendly shale inhibitors instead of KCl.

Table 4: NDDF additives: Concentration and purpose of use.

Additive	W/V mixed with base water	Purpose
Common salt	15%	Stabilization of water-sensitive shales and inhibition of the formation of gas hydrates.
KCl	5-8%	Shale inhibitor.
PGS	1.00%	Increasing the viscosity of the drilling mud and reducing the fluid loss.
XC-polymer	0.50%	Viscosifier-as it gives the fluid thixotropic properties while being bio-degradable.
PAC-R	8-10%	Filtration reduction, anti-salt, anti-collapse, and high-temperature resistance.

$CaCO_3$	0.10%	Bridging agent-calcium carbonate is acid soluble and used to form removable filter cake. It is also used to impart higher specific gravity to NDDF.
Biocide	0.02%	Bactericides to control bacteria that attacks the polymers in drilling fluid.

Fluid loss control and rheological properties improvements

The fluid loss into the formations causes formation damage, borehole instability and hinders the drilling performance. The decrease in rheological characteristics influences carrying capacity. So, in order to prevent these problems, proper fluid loss control must be achieved while improving the rheological properties. Various approaches regarding fluid loss control and rheological properties are mentioned below.

Environment friendly additive approach: Many researchers have taken environment friendly approach to design a WBDF using natural substances, bio-products as fluid loss control agent and rheology modifier. The main advantages of these additives are being eco-friendly, easier to prepare, low cost for formulation and disposal after use. Table 5 shows the various recent applications of environmentally friendly additives and their effects in fluid loss, rheological properties.

Recent advances using nanoparticles: In recent years, many approaches have been taken to control the fluid loss. The most preferred approach in terms of performance was to use nanoparticles to reduce the filtrate loss. In one approach, Iron Oxide (Fe_2O_3) and graphite nanoparticles were used and the yield point and viscosity were increased significantly with iron oxide compared to graphite. The addition of nanoparticles maintained the stability of drilling muds at HPHT conditions and resulted in a stable rheological profile. A significant reduction in the fluid loss was also observed with iron oxide resulting in the lowest fluid loss compared to base and graphite mixed drilling muds (Table 5). Some of the other applications of nanoparticles to reduce fluid loss are shown in Table 6. However, even though nanoparticles are performing better to reduce the fluid loss, its impact on environment has not been studied in the pre-existing approaches. So, the future focus should be on the environmental impact of the nanoparticle-based drilling fluid [20].

Table 5: Environment friendly additive: Effects in fluid loss and rheology.

Author	Additive used	Concentrations	Effect on rheology	Effect on fluid loss
Al-Hameedi et al.	Black Sunflower Seeds' Shell Powder (BSSSP)	0.5%, 1.5%, and 2.5%	BSSSP has a negligible impact on PV and no effect for the concentration change. However, BSSSP additives significantly increased the yield point.	2.5% BSSSP showed the most reduction in fluid loss in 7.5 ml as compared to 8.5 ml in 0.5% BSSSP.
Asma Nour et al.	Potato and corn starch	(0.6, 1.2, and 2.0%) in addition to potassium chloride (1.5, 3.0, and 4.5%).	Enhanced the rheological properties	In average, reduced the fluid loss by (20.66% and 26.66%) and the filter cake thickness by (6.33% and 17.77).
Awl et al.	Broad Bean Peel Powder (BBPP)	Fine and medium sizes 1%, 2%, and 3%	BBPP enhanced its rheological characteristics (Plastic viscosity, gel strength). It has negligible effect on other properties, including mud weight and yield point.	Fine sized particles were more effective in reducing the filter cake thickness and fluid loss from 1.75 mm and 20.4 mL to 1.0 mm and 13.3 mL, respectively.
Murtaza et al.	Okra (Hibiscus esculents)	(0.25, 0.5, and 1)% in a clay free water-based drilling fluid formulation.	Okra has less impact on rheological properties compared to conventional starch.	Addition of 1 % okra solution was found to reduce 20% fluid loss.

Onuh et al.	Coconut shell and corn cobs	(2, 4, 6, 8, 10) gm each and mixture of both in equal amount was added in 350 ml drilling fluid sample.	No significant change in rheology.	Addition of 10 g of each showed the most reduction in fluid loss, corncob showed 18 ml while coconut shell showed 20 ml fluid loss. Combination of these two showed improved result with 16 ml fluid loss.
Zhou et al.	Wild Jujube pit powder	(0, 0.5, 1, 3, 5)%	WJSS can increase the viscosity and yield point.	With the increase in the concentration of WJPP, the filtration loss of the drilling fluid decreased first and then increased. At 3% WJPP, the fluid loss of the drilling fluid was the lowest and the filtration rate was 42.5%.

Table 6: Nanoparticles: Effects in fluid loss.

Author	Nanoparticles	Effect observed
Aftab et al.	ZnO/polymer nanocomposite	Under HPHT condition 1.0 g of ZnO nanoparticle reduced the filtrate loss by 14%.
Halali et al.	Carbon nanotubes	CNT could reduce the filtration by over 93.3% at HPHT conditions.
Ismail et al.	Multi-Walled Carbon Nanotube (MWCNT)	Filtrate loss volume of Sarapar drilling fluid was reduced by 19% after aging at 250°F for 16 hours.
Ismail et al.	Nanosilica and MWCNT	0.01 g of nano silica and MWCNT reduced filtrate loss by 4% and 10%, respectively.
Medhi et al.	Nano alumina	1% Al_2O_3 NP drilling fluid reduced the filtrate loss by 42.5% compared to base drilling fluid.
Murtaza et al.	Iron Oxide (Fe_2O_3) and graphite	Compared to graphite, iron oxide showed significant reduction in fluid loss.
Nizamani et al.	Titania-bentonite nanocomposite	API filtrate loss volume and high-pressure high temperature filtrate loss volume were slightly reduced by 10%, and 9.2%.

CONCLUSION

There have been many attempts to design environmentally friendly drilling fluid whose main goal was to lower the impact of hazardous chemicals on the environment as well as trying to reduce the cost of drilling. Generally, environmentally friendly additives are used to replace the various chemicals used as drilling fluid additives. While choosing the environmentally friendly additives, the selection criteria involve availability of raw materials in abundance near the oil field as well as low cost. Most of the approaches involve use of polymers to control the various properties like thermal stability improvement, enhancing of mud rheological parameters and reducing fluid loss, filter cake thickness. However, it was observed that focus on fluid loss reduction and rheology improvements is more than the other properties.

Recent developments use nanoparticles for drilling fluid performance enhancement. Nanoparticles have been used to improve thermal resistance of drilling fluid, as a shale inhibitor and to reduce the filtrate loss. The performance of nanoparticle-based drilling fluid is better than the conventional drilling fluids. However, the environmental aspect is missing in many of nanoparticle-based approaches and future research should focus on this aspect.

After the completion of drilling operations, the drilling fluids used in the drilling process along with additives, drill cuttings, residue oil and water are treated as waste drilling fluid and generally discarded in nearby soil or water, causing harm to the environment. Due to this practice, the disposing of waste drilling fluid near the well site is a serious environmental issue. Oil and gas installations usually produce water containing heavy metals, dispersed oil, aromatic hydrocarbons and naturally occurring radioactive materials. While technology already exists to re-inject the produced water, it has to be treated first. Using environmentally safe materials in the source drilling fluid formulation can drastically reduce the disposal issues, while also reducing the treatment cost.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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